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R. N. Boyd, M. Famiano, B. S. Meyer, Y. Motizuki, T. Kajino, I. U. Roederer

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R.N. Boyd

Physics and Life Sciences, L-050, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

`boyd11@llnl.gov`

M.A. Famiano

Dept. of Physics, Western Michigan University, 1903 W. Michigan Avenue, Kalamazoo, MI 49008-5252, USA

B.S. Meyer

Dept. of Physics and Astronomy, Clemson University, 118 Kinard Laboratory, Clemson, SC 29634-0978 USA

Y. Motizuki

RIKEN Nishina Center, Hirosawa 2-1, Wako, 351-0198 Japan

T. Kajino[1]

National Astronomical Observatory of Japan, 2-21-1 Mitaka, Tokyo, 181-8588, Japan

and

I.U. Roederer

Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA

Received ____________________; accepted ____________________

[1]Dept. of Astronomy, Graduate School of Science; Univ. of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

ABSTRACT

Nucleosynthesis of heavy nuclei in metal poor stars is generally thought to occur via the r-process, and the similarity of the abundances in many of these stars confirms its basic characteristics. However, a significant number of metal poor stars do not share this standard r-process template. In this Letter we suggest that the nuclides observed in many of these stars are produced by the r-process, but that it is prevented from running to completion in more massive stars by collapse to black holes before the r-process is completed, creating a "truncated r-process," or "tr-process." We find that the observed fraction of tr-process stars is qualitatively what one would expect from the initial mass function, and that an apparent sharp truncation observed at around mass 160 could result from a combination of collapses to black holes and the difficulty of observing the higher mass rare earths. We test the tr-process hypothesis with r-process calculations that are terminated part way through the process. We find qualitative agreement between observation and theory when black hole collapse and observational realities are taken into account.

Subject headings: stars: Population II — nucleosynthesis — black hole physics

1. Introduction

The r-process has been understood for many years to (1) synthesize half the nuclides heavier than iron, (2) synthesize all of the nuclides heavier than ^{209}Bi, and (3) be primary in the sense that its nucleosynthesis does not appear to depend on preexisting nuclides (Burbidge et al. 1957; Woosley et al. 1994; Wallerstein et al. 1997; Farouqi et al. 2009). In this latter context, its production of the heavier r-process nuclides in many metal poor stars appears to be very similar (Sneden & Cowan 2003), and it also produces relative r-process abundances that are essentially the same as those found in more modern stars. A standard interpretation of the r-process suggests that it occurs in the neutrino wind that emanates from core-collapse supernovae (Woosley et al. 1994; Takahazhi, Witti, & Janka 1994; Farouqi et al. 2009), although that interpretation is not without its issues (Meyer, McLaughlin, & Fuller 1998; Roberts, Woosley, & Hoffman 2010).

At the same time, other metal poor stars exhibit some of the features of r-process nucleosynthesis, but their abundances represent a surprisingly poor match with the "standard" abundance template (Aoki et al. 2000; Honda et al. 2007; Roederer et al. 2010a), perhaps most frequently identified as that observed in CS-22892-052 (Sneden & Cowan 2003). A recent paper (Roederer et al. 2010a) has summarized the situation that exists for metal poor stars. That paper seems to suggest that a distribution of r-process abundances exists in metal poor stars, with some resembling the standard abundance set, but with a significant fraction of stars having abundances that do not match the standard template. These latter stars appear to favor the lighter r-process nuclides at varying levels, and many seem to terminate around Dy, that is, around mass 160.

In this Letter we point out that the abundance patterns observed for the stars that do not fit the standard r-process template could be produced by stars that are sufficiently massive that their supernovae first produce neutron stars, but the infall that occurs following the formation of the neutron star subsequently results in collapse to a black hole - so called “fallback supernovae.” This class of stars spans a mass range from roughly 25 to 40 solar masses (Heger et al. 1992) for low-metallicity stars. It is known that many core-collapse supernovae explode asymmetrically, i.e., they produce a “kick” to their neutron star, which results in its recoiling from the nebula produced by the supernova at high speeds - hundreds of km/s (Arzoumanian et al. 2002). Although the dynamics would be complicated, this might be expected to produce a trail of the r-produce synthesis along the path of the recoiling neutron star. However, when the neutron star collapsed to a black hole the r-process enrichment of the interstellar medium would cease, terminating either when the r-processed regions were swallowed by the black hole, or when the electron antineutrinos fell below the event horizon (Sasaqui, Kajino, & Balantekin 2005). Thus, this truncated r-process, or tr-process, nucleosynthesis would terminate at different stages of that process, depending on the precise time at which the black hole prevented further r-process production or emission of nuclides into the interstellar medium.

It might be expected that the time of the collapse to the black hole would vary with stellar mass, which would negate the possibility of a single time at which the r-process would be truncated. But we suggest that the delayed collapse to the black hole, combined with another effect, namely, the difficulties in observing the higher mass rare earths, could produce the cutoff in the r-process distributions observed around 160 u.

2. Neutrino Wind Model of the r-Process

The neutrino wind scenario of the r-process is thought to synthesize its products beginning with the r-process seeds, apparently the nuclei resulting from the nuclear statistical equilibrium that occurs as the hot core of the star cools, and appears to include nuclei that are close to the nuclear valley of stability up to masses just below 100 u (Woosley et al. 1994). The high neutron density that must accompany the r-process then promotes those seed nuclei successively to higher mass, pausing at the neutron closed shells at 82 and then 126 neutrons, and thereby producing the r-process abundance peaks at A$\sim$130 and 195 u (Woosley et al. 1994; Wanajo et al. 2002).

Although no calculation has yet conclusively demonstrated that core-collapse supernovae are the site of the r-process, many of the requisite conditions apparently exist in that site. What is apparently required of the codes is three-dimensional hydrodynamics, so that the instabilities that must exist can prevail, so as to generate the neutron star kicks (Burrows et al. 2006; Guilet, Sato, & Foglizzo 2010); to include all of the detailed neutrino physics (Burrows & Thomson 2002; Roberts, Woosley, & Hoffman 2010; Liebendoerfer et al. 2005) to produce the required neutron density and expel the newly synthesized material from the star as it is produced; and contain all the nuclear reaction details of the r-process. Current supernova models do not naturally produce the parameters required to produce a successful r-process, most notably the entropy. However, results from multidimensional hydrodynamics calculations suggest that the instabilities resulting from those calculations may ultimately be shown to produce the required entropy (Burrows et al. 2006). We will therefore assume that core-collapse supernovae are at least one of the sites of the r-process, and that we know enough about the required parameters to generate a successful r-process.

3. Model Calculations

Thus we have run tr-process calculations by assuming that the required parameters can be produced by the hydrodynamics if one could perform a full scale calculation, rather than attempting a first-principles calculation. We have used a network code based on libnucnet, a library of C codes for storing and managing nuclear reaction networks (Meyer & Adams 2007). For the calculations, it was assumed that the entropy was a constant and was sufficiently high to reproduce the r-process abundances to a good approximation. Nuclear reactions during the r-process generate entropy, but the amount generated is typically a small fraction of the total in neutrino-driven wind environments (Meyer & Brown 1997). One also chooses an initial temperature and an initial electron-to-nucleon ratio Y_e. The code calculates the density ρ_o such that the matter is in nuclear statistical equilibrium at that temperature and Y_e value has the specified entropy per nucleon. The code allows the material to expand following a density vs. time function ρ(t) and radius vs. time function r(t).

The code's default functions are based on an assumption of mass flow from a spherically symmetric source. Thus

$$\frac{dM}{dt} = 4\pi r^2 v\rho \tag{1}$$

where dM/dt is the mass-loss rate and v is the outflow velocity. The default functions are derived from the assumption that M and v are constant in time, or

$$R(t) = r_o + v_o t \tag{2}$$

where r_o is the initial radius of the outflowing matter, v_o is the constant velocity, and

$$\frac{dM}{dt} = 4\pi r_o^2 \left(1 + \frac{t}{\tau}\right)^2 \rho \tag{3}$$

where τ=r_o/v_o. Since we assume dM/dt to be constant,

$$\rho(t) = \frac{\rho_o}{\left(1 + \frac{t}{\tau}\right)^2} \tag{4}$$

As noted above, we have terminated the r-process calculation at various processing times to see what distribution of nuclides would be produced if the r-process were terminated before it ran to completion. The various models were parametrized by the initial electron fraction Y_e (which ranged from 0.35 to 0.47), the initial temperature T_9 (which ranged from 43 to 47), the initial density ρ, (which ranged from 1.375×10^8 to 1.525×10^8 g cm^{-3}), and the expansion timescale for adiabatic expansion (which ranged from 0.03 to 0.06 seconds). For expansion in the hot bubble with neutrino heating, the neutrino heating was implemented as an external parameter resulting in a non-adiabatic expansion of the hot-bubble region. In this case, the network calculation environment (temperature and density) was coupled to the output of a hydrodynamics calculation (Otsuki et al. 2000). A final model was simulated with a somewhat later hot-bubble expansion.

One calculation that gave a reasonable representation of the r-process abundances, but which was terminated at intermediate times prior to its completion of its r-process, is shown in Figure 1. The calculations assumed values for T_9, ρ, Y_e, and τ of 45, 1.375×10^8, 0.40, and 0.06. The truncation times for the different colored curves are given in the caption, but they show that the r-process nucleosynthesis moves relatively smoothly through the nuclides between the mass 130 and 195 abundance peaks, as terminating the r-process flow shifts the highest mass produced up to that time uniformly to heavier nuclides.

The results of most of the calculations done for which the r-process that produced the mass 195 peak looked qualitatively similar to those shown in fig. 1, and bore qualitative similarity to the standard r-process abundance set (Käppeler, Beer, & Wisshak 1989), also shown in fig. 1. In some cases, though, the processing was slower prior to the rapid expansion, resulting in a slower processing time through the rare earth region prior to freezeout. Thus the actual truncation times should not be taken too seriously; one calculation that produced very similar results to those shown in fig. 1 had comparable mass cutoffs at times that were about twice those given in the fig. 1 caption.

To test the robustness of our results, we also applied a second approach to test the general concept behind the tr-process. This approach utilized the basic idea behind the study of Woosley et al. (1994) for a spherically symmetric supernova expansion model. In that study, a succession of 40 "trajectories" (that is, thin shells), all assumed to have originated deep within the star, but having initially different conditions of density, temperature, entropy, and electron fraction, were processed in the neutrino bubble, and then emitted, thus contributing to the total r-process nucleosynthesis. The neutrino bubble was evolving in time, so that the conditions under which the individual trajectories were processed changed with the identity of the trajectory. The same idea that was assumed above could be applied here also, namely, that the different trajectories were emitted from the star successively, but ceased to be emitted when the collapse to the black hole occurred. This would be consistent with Woosley et al. (1994), who assumed successive emissions of the trajectories to generate what turned out to be a good representation of the Solar r-process abundances.

The simulation of Woosley et al. (1994) that produced a good r-process representation began with trajectory number 24 and summed the nucleosynthesis from the remaining 16 elements. This was argued to be a reasonable approach because the entropy of the processed trajectories increased with trajectory number, and the highest entropy points would most likely be at the top of the mass distribution after processing. Thus these would be emitted into the interstellar medium. We also began with trajectory 24, and performed a mass weighted sum of the nucleosynthesis from the trajectories up to some higher number trajectory to observe the resulting nucleosynthesis when the trajectories beyond our maximum trajectory were assumed to be consumed by the collapse to a black hole. This produced a result similar to that of Woosley et al. (1994) when all trajectories from 24 to 40 were included. The results are shown in Figure 2. There it can be seen that truncating the r-process at increasing times does terminate the r-process nucleosynthesis at increasingly higher nuclear mass. Note that although the curve representing trajectories 24 through 31 does reach the mass 195u peak, the abundance produced in that calculation is nearly two orders of magnitude below that of the full r-process, so would not be observable. The abundances for that calculation would therefore appear observationally to terminate at a mass of about 140 u.

Our r-process nucleosynthesis network calculations were performed for trajectories 24 - 40 in the Woosley et al. (1994) hydrodynamics model using the reaction network described above. For each trajectory, reaction network calculations were performed for T_9 <2.5 using initial abundances derived from the Woosley et al. (1994) results. Our calculations were simplified by assuming an initial abundance of massive nuclei from a single nucleus heavy seed with a mass A equal to the average mass at T_9=2.5 and an atomic number derived from the average mass number, the Y_e, and the neutron and alpha mass fractions at T_9=2.5 in Woosley et al. (1994). An adiabatic expansion was assumed for each trajectory in the nucleosynthesis, again consistent with the approach of Woosley et al. (1994). For each trajectory the calculation was continued until freezeout and several seconds through post-processing. Our representation of the full r-process abundances, shown as the dots in Figures 1 and 2, is not as good as that achieved by Woosley et al. (1994), presumably due to the slight differences in our computational approaches, but our calculations do produce the basic features of the full r-process, namely the mass 130 and 195u peaks.

In Figure 3 we compare several tr-process calculations with the derived elemental abundance pattern in the metal poor halo star HD 122563. This low-metallicity star ([Fe/H] = -2.7) is deficient in the heavy neutron-capture elements (Ba and heavier) relative to the light neutron-capture elements (Sr through Cd) when compared with the scaled Solar r-process pattern. The HD 122563 abundances are a very poor match to the scaled Solar s-process pattern. Its abundance pattern matches the scaled Solar r-process pattern better up to an atomic mass of about 70 (mass of ∼174 u), but even this fit is unsatisfying (Sneden & Parthasarathy 1983; Honda et al. 2006). Stars like HD 122563 may be candidates for enrichment by the tr-process. Figure 3 demonstrates that the tr-process predictions, while far from a perfect match to the individual abundances, can reproduce the relative downward trend in abundance with increasing atomic number seen in some metal poor stars. More exploration of tr-process calculations is obviously needed, but the general trend is encouraging.

4. Probability of Occurence of tr-Process Stars

In principle, a test of the tr-process model would be provided by a large set of data for metal poor stars that spans the masses of the nuclides produced in the r-process from mass $\sim$80 to the heaviest observable nuclides that the r-process synthesizes, usually thorium. Unfortunately this is challenging due to the difficulty of observing the higher mass rare-earth nuclides, starting at mass $\sim$160. Thus all r-process events that terminate at masses between 160 and lead would appear to terminate at mass 160, producing the effect observed by Roederer et al. (2010a).

Any standard initial mass function (IMF) reflects the fact that less-massive stars are more numerous than more-massive stars. Assuming that stars from 8 to 40 solar masses may produce comparable amounts of r-process material, we can use the IMF to estimate the fraction of stars whose r-process may be truncated by collapse to a black hole. We adopt the Salpeter (1954) IMF, for which $dN/dm \propto m^{-2.35}$ for massive stars, where m is the stellar mass in units of the solar mass, and N is the number of stars of a given mass per unit volume. The ratio of the number of stars that would be expected to collapse to black holes (25-40 solar masses) to those expected to collapse to neutron stars (8-25 solar masses) is 0.13 in a well-sampled IMF.

While a number of r-process rich stars (here taken to mean stars with [Eu/Fe] $> +1.0$) have been discovered and studied in detail in the last two decades, these stars constitute a relatively minor fraction of all metal-poor stars. More unbiased samples (McWilliam et al.

1995; Barklem et al. 2005) find that stars with [Eu/Fe] > +1.0 comprise <10% of all stars with [Fe/H] < -2.0. Figure 11 of Roederer et al. (2010a) suggests that stars with [Eu/Fe] < 0 are candidates for enrichment by a truncated r-process. Difficulties in detecting Eu in metal-poor stars with [Eu/Fe] < 0 make it even more challenging to estimate how numerous these stars are. Ba is more easily detected and may be used to represent Eu and other heavy elements in stars lacking s-process enrichment. From the Ba abundances in the large survey of Barklem et al. (2005) we estimate a lower limit of ∼55% of metal-poor stars as candidates for enrichment by a truncated r-process. This is significantly higher than the 13% derived above assuming a Salpeter IMF, yet Figure 3 demonstrates that a tr-process may be one way to produce the heavy nuclides observed in some metal-poor stars. The discrepancy in these fractions could indicate that additional nucleosynthesis channels, such as those proposed by, e.g., Qian (2008), Farouqi et al. (2009), Wanajo et al (2011), or Nakamura et al. (2011), together with the tr-process may contribute to the chemical enrichment of the early Galaxy. Given that massive stars with short lifetimes will dominate the chemical enrichment at early times, though, the tr-process may very well have been a major source of heavy nuclei at these epochs.

5. Other r-Process Issues

As a possible additional benefit of the tr-process, we note that the stars that were truncated at 0.53 s or less produced no nuclides in the mass 130 peak or beyond. This would have the effect of boosting the yields of the lighter r-process nuclides relative to the heavier ones, filling in the mass 110 to 120 u region. It has been known for some time that r-process calculations that produce a mass 195 u peak underproduce the nuclides in the 110-120 mass region. The r-process nuclides that were even lighter than those were underproduced by an even larger factor, but this would also be consistent with distributed cutoffs of the r-process nucleosynthesis. Thus, again guided by the IMF, but along with the mass dependent cutoff times, the tr-process might potentially solve this troublesome aspect of current r-process analyses (Kratz et al. 2007; Farouqi et al. 2009). Conclusions in this regard, however, must await more detailed analyses.

An obvious test of the tr-process model could occur from renewed effort to observe the higher mass rare earth elements in very metal poor stars with low [Eu/Fe] ratios. If elements in that mass region can be observed, and the tr-process is correct, additional observations would be expected to map out the black hole collapse times over that region. While no doubt challenging, a relationship between observations and black hole collapse times would be of great interest.

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REFERENCES

Aoki, W., Norris, J.E., Ryan, S.G., Beers, T.C., & Ando, H. 2000, ApJ, 536, L97

Arzoumanian, Z., Chernoff, D.F., & Cordes, J.M. 2002, ApJ, 568, 289

Barklem, P.S., Christlieb, N., Beers, T.C., Hill, V., Bessell, M.S., Holmberg, J., Marsteller, B., Rossi, S., Zickgraf, F.-J., & Reimers, D. 2005 A&A, 439, 129

Burbidge, M., Burbidge, G., Fowler, W.A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 547

Burrows, A. & Thomson, T.A. 2002, *Core Collapse of Massive Stars*, ed. by C.L. Fryer, Kluwer Academic Publ.

Burrows, A., Livne, E., Dessart, L., Ott, C.D., & Murphy, J. 2006, ApJ, 640, 878

Farouqi, K., Kratz, K.-L., Pfeiffer, B., Rauscher, T., Thielemann, F.-K., & Truran, J.W. 2009, ApJ, 694, L49

Guilet, J., Sato, J., & Foglizzo, T. 2010, ApJ, 713, 1350

Heger, A., Fryer, C.L., Woosley, S.E., Langer, N., & Hartmann, D.H. 1992, ApJ, 591, 288

Hoffman, R.D., Woosley, S.E., & Qian, Y.-Z. 1997, ApJ, 482, 951

Honda, S., Aoki, W., Ishimaru, Y., Wanajo, S., & Ryan, S.G. 2006, ApJ, 643, 1180

Honda, S., Aoki, W., Ishimaru, Y., & Wanajo, S. 2007, ApJ, 666, 1189

Käppeler, F., Beer, H., & Wisshak, K. 1989, Rep. Prog. Phys., 52, 945

Kratz, K.-L., Farouqi, K., Pfeiffer, B., Truran, J.W., Sneden, C., & Cowan, J.J. 2007, ApJ, 662, 39

Liebendoerfer, M., Rampp, M., Janka, H.-Th. & Mezzacappa, A. 2005, ApJ, 620, 840

McWilliam, A., Preston, G.W., Sneden, C., & Searle, L. 1995, Astron. J., 109, 2757

Meyer, B.S. & Adams, D. C. 2007, Met. Planet. Sci., 42, 5125; see also http://sourceforge.net/projects/libnucnet/

Meyer, B.S. & Brown, J. S. 1997, ApJS, 112, 199

Meyer, B.S., Mathews, G.J., Howard, W.M., Woosley, S.E., & Hoffman, R.D. 1992, ApJ, 399, 656

Meyer, B.S., McLaughlin, G.C., & Fuller, G.M. 1998, Phys. Rev. C, 58, 3696

Nakamura, K., Sato, S. Harikae, S., Kajino, T., & Mathews, G.J. 2011, ApJ (submitted)

Otsuki, K., Tagoshi, H., Kajino, T., & Wanajo, S. 2000, ApJ, 533, 424

Qian, Y.-Z. &Wasserburg, G.J. 2008, ApJ, 687, 272

Roberts, L.F., Woosley, S.E., & Hoffman, R.D. 2010, ApJ (submitted)

Roberts, L., & Woosley, S.E., private communication

Roederer, I.U., Kratz, K.-L., Frebel, A., Christlieb, N., Pfeiffer, B., Cowan, J.J., & Sneden, C. 2009, ApJ, 698, 1963

Roederer, I.U., Cowan, J.J., Karakas, A.I., Kratz, K.-L., Lugaro, M., Simmerer, J., Farouqi, K., & Sneden, C. 2010a, ApJ, 724, 975

Roederer, I.U., Sneden, C., Lawler, J.E., & Cowan, J.J. 2010b, ApJ, 714, L123

Salpeter, E.E. 1954, Australian J. Phys., 7, 373

Sasaqui, T., Kajino, T., & Balantekin, A.B. 2005, ApJ, 634, 534

Schorck, T., et al. 2009, A&A, 507, 817

Sneden, C. & Parthasarathy, M. 1983, ApJ, 267, 757

Sneden, C., Cowan, J.J., Lawler, J.E. Ivans, I.I. Burles, S., Beers, T.C., Primas, F., Hill, V., Truran, J.W., Fuller, G.M., Pfeiffer, B., & Kratz, K.-L. 2003, ApJ, 591, 936

Sneden C. & Cowan, J.J. 2003, Science, 299, 70

Takahashi, K., Witti, J., & Janka, H.-Th. 1994, A&A, 286, 857

Wallerstein, G. et al. 1997, Rev. Mod. Phys., 69, 995

Wanajo, S., Itoh, N., Ishimaru, Y., Nozawa, S., & Beers, T. 2002, ApJ, 577, 853

Wanajo, S., Janka, H.-J., & Kubono, S. 2011, ApJ, 729, 46

Woosley, S.E., Wilson, J.R., Mathews, G.J., Hoffman, R.D., & Meyer, B.S. 1994, ApJ, 433, 229

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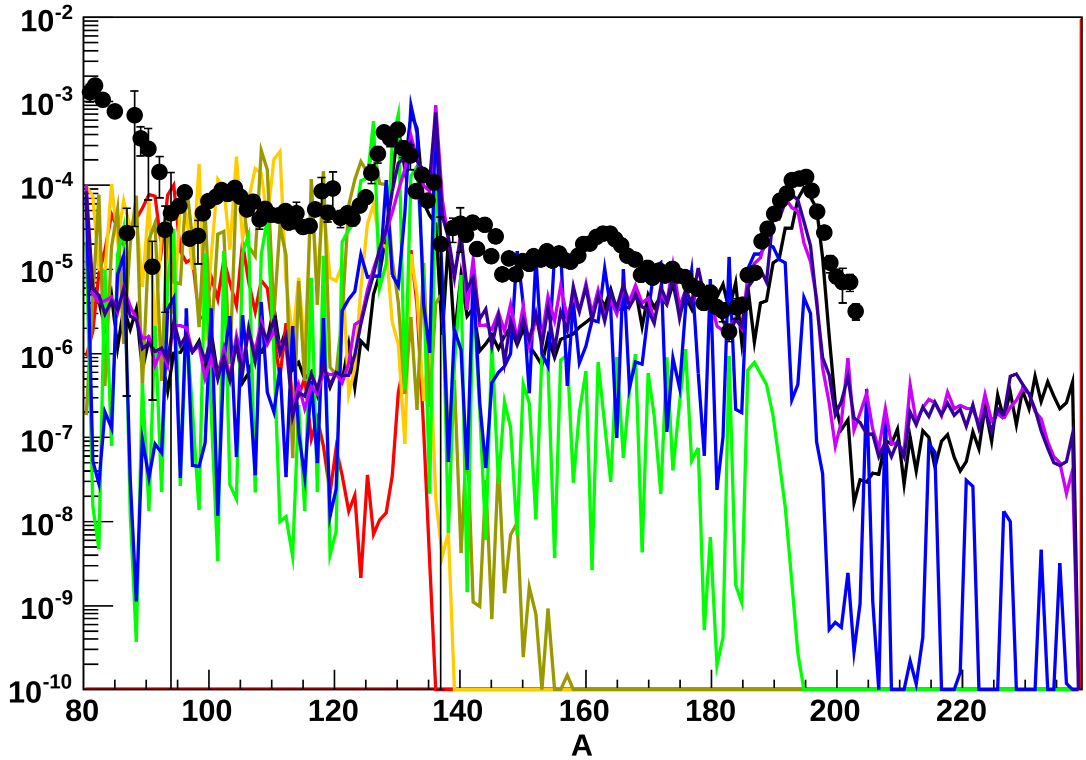

Fig. 1.— r-process production for truncated r-process runs. The times of truncation are: red, 0.43 s; orange, 0.51 s; yellow, 0.57 s; green,0.69 s; blue, 0.82 s; purple, 0.95 s; dark purple, 1.0 s; black, 1.04 s. Solar r-process abundances(Käppeler, Beer, & Wisshak 1989) are shown as dots.

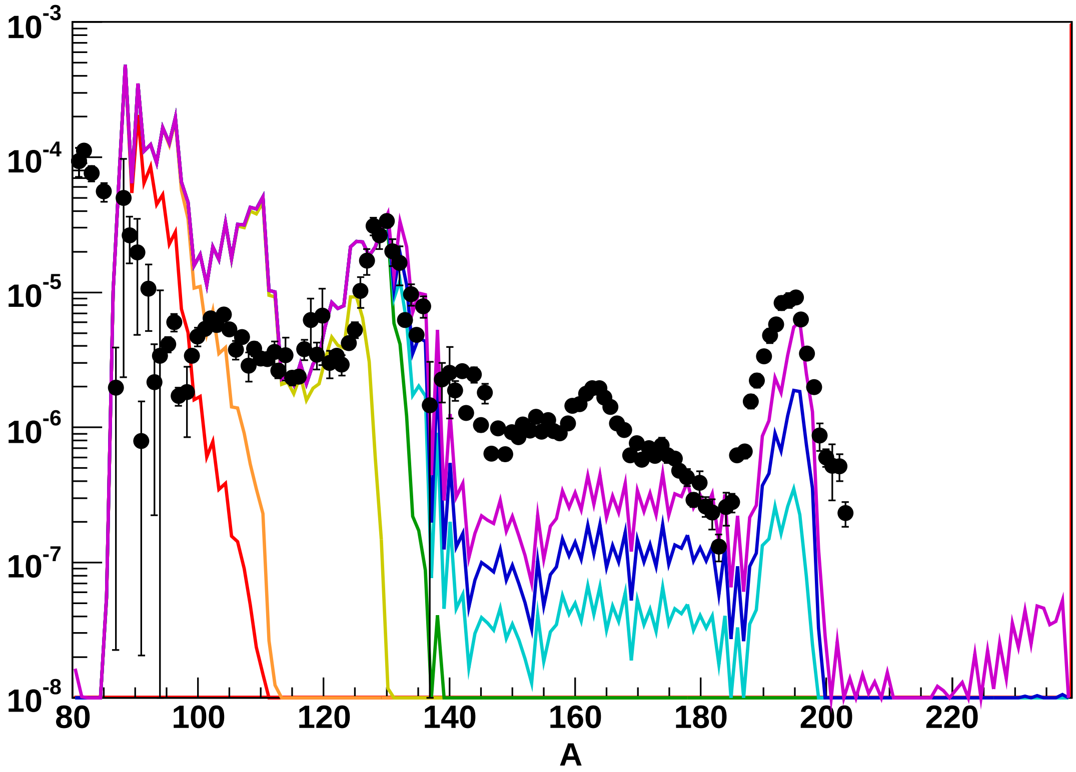

Fig. 2.— . r-Process calculations using the trajectories from Woosley et al. (1994), but summing the results from trajectory number 24 to some later trajectory, as was done in Woosley et al. (1994). The successive curves include trajectory 24 (2.2400 s), 24 through 26 (2.7564 s), 24 through 28 (4.4605 s), 24 through 30 (6.7476 s), 24 through 31 (8.5101 s), 24 through 32 (9.6876 s), and 24 through 40 (16.1677 s), where the emission times of the latest trajectory in each sum are as indicated. The sums to higher number trajectories make both the mass 130 and 195 r-process peaks, and the sum through trajectory 40 comes closest to representing the Solar r-process abundances (Käppeler, Beer, & Wisshak 1989), shown as the dots.

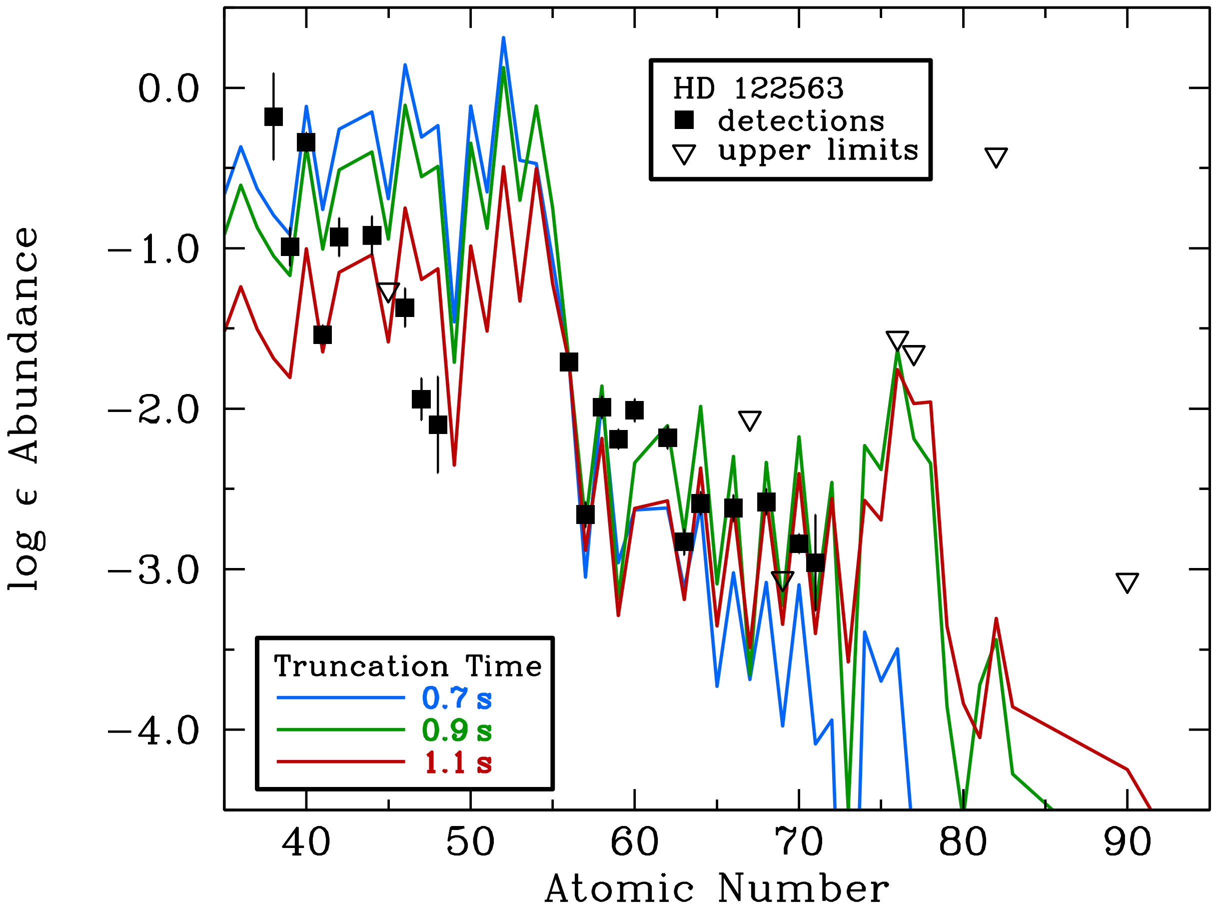

Fig. 3.— Comparison of tr-process predictions, using the formalism adapted from Woosley et al. (1994), for three truncation times with abundances in the metal-poor star HD 122563. Observational data are from Honda et al. (2006) and Roederer et al. (2009, 2010b). The predictions are scaled to the Ba abundance (Z=56).